

Geometry Modeling and Grid Generation for Computational Aerodynamic Simulations around Iced Airfoils and Wings

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Abstract

Issues associated with analysis of "icing effects" on airfoil and wing performances are discussed, along with accomplishments and efforts to overcome difficulties with ice. Because of infinite variations of ice shapes and their high degree of complexity, computational "icing effects" studies using available software tools must address many difficulties in geometry acquisition and modeling, grid generation, and flow simulation. The value of each technology component needs to be weighed from the perspective of the entire analysis process, from geometry to flow simulation. Even though CFD codes are yet to be validated for flows over iced airfoils and wings, numerical simulation, when considered together with wind tunnel tests, can provide valuable insights into "icing effects" and advance our understanding of the relationship between ice characteristics and their effects on performance degradation.

Introduction

When airplane wings are contaminated with ice during icing weather conditions, the ice destroys the smooth flow of air, decreasing lift, while increasing drag. As power to propel is raised to compensate for the additional drag, and the nose is lifted to maintain altitude, the angle of attack is increased. In moderate to severe icing conditions, a light airplane wing without any excess heat or boots to prevent or remove ice may stall at a much higher speed and lower angle of attack than normal. Ice contamination on the tail can be more critical, because it has a smaller leading edge radius and chord length than the wings and as a result it can collect two or three times more ice than the wings. The horizontal stabilizer on the tail of the plane balances the tendency of the airplane nose to pitch down by generating downward pressure. However, when the tail stalls due

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to ice accretion, this downward force is decreased or even removed, and the nose of the airplane can pitch down dangerously. It can roll or pitch uncontrollably, and recovery of control can become difficult. Thus, analysis of the aerodynamic performance of iced airfoils and wings is important, for ice contamination can become a safety issue for an airplane.

This paper discusses some of the unique issues that aircraft icing poses when the icing effects on airfoil and wing performances are to be simulated by computation. The computational icing effects study involves geometry acquisition/modeling, grid generation, and numerical aerodynamic simulation. The paper consists of two main sections: icing effects study in two-dimensional airfoils, and that in three-dimensional wings. In each section, progress made and issues identified in geometry acquisition/modeling, grid generation, and aerodynamic simulation are discussed.

Icing effects on aerodynamics can be studied experimentally as well as computationally as shown in Figure 1. Until physical models such as turbulence models are validated for flow separation regions behind ice horns and unsteady flows, both computations and experiments can be conducted in a complementary way to each other. Understanding of relationships between ice characteristics and their effects on airfoil and wing performance needs to be advanced. Therefore, ice shape characterization is an important element of the study.

Icing Effects on Airfoil Performance: Two Dimensional (2D) Issues

Geometry acquisition and modeling of ice present a challenge even in two dimensions [1][2]. Figure 2 shows two sample 2D ice shapes as an illustration: a moderate and a complex. Geometry data such as these can come from the Icing Research Tunnel (IRT) where ice accretion takes place under a controlled icing condition and for a specified duration. The iced wing is then traced at various span-wise locations and digitized for 2D data [2]. Geometry data also can come from flights of aircrafts through icing condition and ice accretion prediction codes. Yet, there is another source of geometry data. Iced wings can be scanned by 3D laser scanner, which provides point cloud data, from which two-dimensional cross sections can be obtained. Scanning is not always easy for ice on swept wings because it often has deep and narrow cavities.

The data obtained in the harsh environment of the IRT needs to be examined and prepared for grid generation [1]. The digitized data on the iced part of airfoils alone can easily be 500-1000 coordinate points to represent the ice geometry, and may need to be re-discretized for grid generation. It has been found that proper modeling of the iced surface as well as a grid sensitivity study is essential

for the accurate prediction of aerodynamic properties [2][3]. Controlled smoothing with very small tolerance (i.e. using implicit local control functions by positioning one control point on each digitized data point) permits researchers to maintain fidelity of geometry within a small tolerance while allowing them to redistribute points on the curve as needed for grid generation and flow simulation. Ice surfaces can be further smoothed in a controlled manner by reducing the number of control points if desired [3].

Figure 3 shows ice shape characteristics that can be easily measured interactively. Since ice shapes are numerous, parametric study using artificial ice shapes can be a fruitful tool in advancing our understanding of the relationship between ice characteristics and their effect on airfoil performance. With artificial ice shapes, researchers can easily change characteristics of artificial ice for parametric studies. In addition, artificial ice shapes can be used to study the effects of ice roughness (Figure 4). The importance of ice shape characteristics is evident in reference [4] and the FAA "12A Working Group" activity to address critical ice-shape issues.

Approaches for grid generation raise many questions for iced airfoils such as the complex one shown in figure 2. Flow fields over this kind of iced airfoils can have re-circulation zones that change as angle of attack (AOA) increases with eventual flow separation. Finding a performance map (Lift vs. AOA and Drag vs. AOA) is of interest, for the change of the stall angle of the airfoil with ice is critical for safety. Regions behind horns and boundary layer must be resolved to capture viscous effects. Which grid generation technology is best for icing aero simulation in terms of efficiency and accuracy? In other words, which grid technology can best contribute to the overall CFD process including flow simulation? Each grid technology has its strengths and weaknesses. Isotropic triangular grids can easily be generated for even the complex ice shown in Figure 2, and can provide good quality cells. However, it requires an excessive number of surface points to provide necessary grid density in viscous regions, and flow simulation on this grid would be computationally expensive. Anisotropic triangular grids can provide grid economy and the flexibility that requires good grid resolution with ice. However, solution accuracy due to grid skewness needs to be evaluated since the spatial scales of the viscous flow in the boundary layer and circulation flow in concave regions of ice require different aspect ratio cells. Another question that needs to be addressed for any unstructured grid is how to control the grid density where needed (e.g., region behind the upper horn and feather). Hybrid grid can provide the merits of the structured as well as the unstructured [5]. However, hybrid grid generation for numerous ice shapes can be a challenging task, and flow solvers that run on hybrid grids are expected to be less efficient than those running on structured grids. This needs to be further investigated.

Viscous flow simulation on a structured grid is known to be more efficient than that on an unstructured one. And with the well-ordered multi-block structured grid, the control of grid density can be achieved more easily than with other grid generation approaches. However, structured grid generation using state-of-the-art grid generators has proven to be extremely difficult for complex ice shapes. In 2D, however, it is possible to overcome the difficulty of structured grid generation for ice while having the efficiency of flow simulation on the structured grid. In addition, the well-ordered structured grid provides control over grid refinement that is required to obtain accurate solutions [1][6]. To overcome the difficulty of structured grid generation, ice shapes are grouped in a number of classes and then blocking is automated. The automation of blocking is achieved by finding block corner points using a convex hull, and block boundaries are modified as Bezier curves as the separation region grows with increasing AOA. [1]

Two-dimensional flow simulations over iced airfoils were performed with single inner-block structured grids [7][8] as well as multi-block structured grids [9]. As AOA approaches stall angle, convergence requires more iterations. Because CFD solutions depend on grid quality and the turbulence model, grid sensitivity studies are essential, and comparison of computed with experimental results are needed until CFD codes are validated for icing problems [2]. Validation of flow codes will require extensive flow field test data identifying valid turbulence models for separated flows with ice.

A preliminary study [8] with the moderate ice in Figure 2 raised a question whether the application CFD code "WIND" [10] can provide adequate converging solutions on multi-block structured grids. In reference [8], the flow domain around the ice airfoil is first divided into two overlapping blocks — an outer block and an inner block—as shown in the top-left of Figure 5. To examine WIND for convergence issue as well as performance and accuracy on blocked structured grids, the single inner block of the reference [8] is divided into 5 blocks including one wrap-around block as shown in the lower-left picture of figure 5. The WIND code ran three structured grid cases: (1) a single inner block case of [8], (2) an abutting multiple inner block case (Figure 5), and (3) an overlapping multiple inner block case where the inner block boundaries overlapped over two grid points. For this exercise, the shear stress turbulence model and zero angle of attack were used.

Figure 6 shows the history of the convergence of the L2 norm of the residual of the flow equations. The convergence histories for the multi-block simulations are averages over all the blocks of the inner grid. Furthermore, the convergence histories have been filtered using a running average to reduce the high-

frequency oscillations of the residuals to better show the overall variation of the residuals. Dividing the single inner block into five separate blocks resulted in the convergence not dropping to the level observed with the single-block simulation. In addition, high-frequency oscillations were greater for the multi-block simulation. Further study is planned to examine effects of block boundaries such as the wrap-around block boundary that extends through recirculating zones behind the ice horns. Overlapping the zones allowed a noticeable drop in the residual and reduced the oscillations. WIND performs the iterations of the flow equations for each block and then transfers information between the blocks at the end of each cycle, which usually consists of 5 iterations. The information exchanged includes flux information. The exchange of turbulence information is not as sophisticated, and may explain the differences in the drop of the residuals.

The convergence rates of the three simulations were essentially the same and the monitoring of the lift and drag coefficients with number of iterations further confirmed this fact. The multiple-inner-block simulation with matching block boundaries required about 7.59% more CPU time than the single-inner-block simulation to run the same number of iterations. However, the multi-block simulation had 2.72% more grid points due to the blocking. Per grid point, the multi-block simulation required 4.74% more CPU time than the single-block simulation. Of more importance than the convergence of the residual is the differences in the lift and drag coefficients of the three simulations, which are presented in Table 1. Results of multiple inner-block cases are compared with those of single inner-block case. Computed results of single inner-block case are compared with experimental data in [8] and that comparison is not repeated here. As can be seen, overlapping the blocks improves the information transfer across blocks such that the lift coefficients are essentially the same as the single-block simulation. The drag coefficients still have considerable differences. This may be due to the differences in the transfer of turbulence information across block boundaries. The general conclusion to draw from these studies is that when multiple blocks are needed to resolve complicated ice shapes, overlapping the blocks in a contiguous manner will improve convergence and reduce errors in the transfer of flow information across block boundaries.

Table 1. Comparison of lift and drag coefficients for the CFD simulations.

Grid	C_l	C_d
Single inner block	0.432	0.0277
Multiple inner block - matching	0.450 (4.17%)	0.0333 (20.22%)
Multiple inner block - overlapping	0.429 (-0.69%)	0.0303 (9.39%)

Icing Effects on Wing Performance: Three Dimensional (3D) Issues

Three-dimensional iced wing surfaces can be represented by a Non-Uniform Rational B-Spline, commonly referred to as NURBS, through the process shown in Figure 7: from an iced wing section to point cloud data to 2D cross sections to 3D NURBS surface by lofting [11]. For ice shapes with various conic shapes, twisted ridges and valleys, and narrow concave regions, fidelity of ice surfaces have to be relaxed within a certain tolerance in the lofting process due to overshooting and undershooting. Because of the optical property of ice, scanners often introduce some points (noise) that are not on the real surface. The noise has to be removed in 2D cross sections before the 3D NURBS surface is defined by lofting. Ice on swept wings can be very complex [12]. In such cases, optical scanning can be more involved or even other approaches may be employed: slicing the iced wing model at as many span wise locations as desired and then digitizing the slices. Understanding of relationships between 3D ice characteristics and their effects on wing performance is important since many iced wing geometries are highly 3D. However, characterizing 3D ice remains as an open issue. Artificial ice can play a helpful role in understanding ice characteristics and their effects on wing performance because of the complexity of numerous real 3D ice shapes.

Grid generation over wings with moderately complex ice such as the one shown in Figure 7 poses a great challenge. Structured grid generation will be impractical for three-dimensional iced wings, because they often have numerous conic shapes, twisted ridges along the span-wise direction, and concave regions. On the other hand, an unstructured tetrahedral grid for an entire flow domain can be computationally very expensive. With an unstructured grid, quality control including grid-density control needs to be addressed. The point density control through "point and line sources" as suggested in [13] may not be sufficient for iced wings because density control in volumetric regions may be needed behind prominent 3D ice rather than in areas or along lines. Since most ice accretes on front parts of the wings, use of hybrid grids [5] can save computational time for flow simulations. Grid generation in narrow deep valleys, and around sharp twisted ridges and various isolated conic shapes of ice will be difficult for any grid technology.

Numerical flow simulation over wings with complex, natural ice does pose a great challenge because, at this time, the geometry modeling and grid generation cannot be done easily using existing software tools. In addition, recent preliminary computation [14] have indicated that icing flow simulation over wings will be computationally very expensive even with current high-end

workstations in parallel. Thus, the 3D flow simulation over iced wings may benefit from massively parallel computing.

Summary

Issues associated with analysis of “icing effects” on airfoil and wing performances have been discussed, along with accomplishments and current efforts to overcome some of the difficulties. Geometry acquisition and modeling of 2D ice on airfoils can be handled with relative ease using an interactive toolkit being developed specifically for ice. In 2D, it is possible to overcome the difficulty of multi-block structured grid generation for airfoils with even complex ice by blocking and overlapping. This then provides the benefits of computational efficiency and accuracy from controlling density of the grid. Hybrid grids may have merits over other single grid approaches, but it has yet to be demonstrated with ice for the entire analysis process. The 3D iced wings present much greater challenges with a higher degree of complexity compared to 2D airfoils. Therefore approaches and tools to be used for 3D geometry acquisition/modeling, grid generation, and flow simulation will be different from those used for 2D cases. Hybrid grid is the most promising for 3D “icing effects” study. Unsteady flow phenomena, which are not discussed in this paper, have yet to be addressed, since flow separations can easily occur with ice.

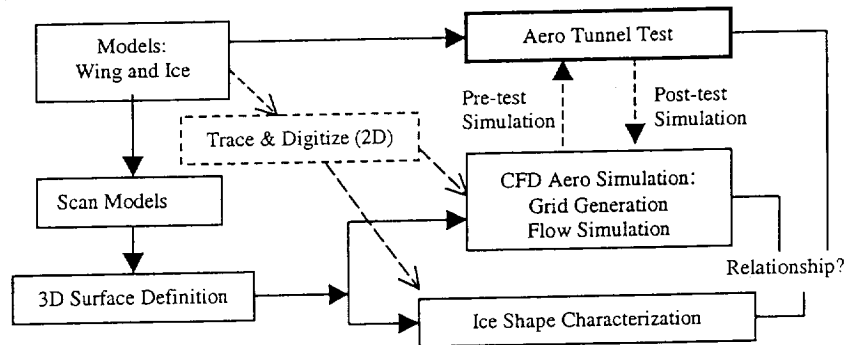


Figure 1. Study of icing effects on performance of airfoils and wings

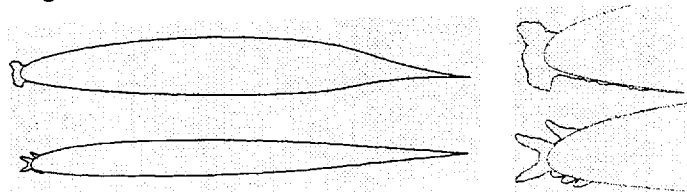


Figure 2. Sample ice shapes: moderate and complex

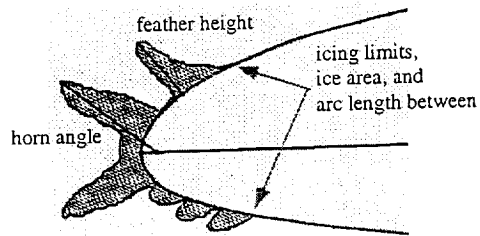
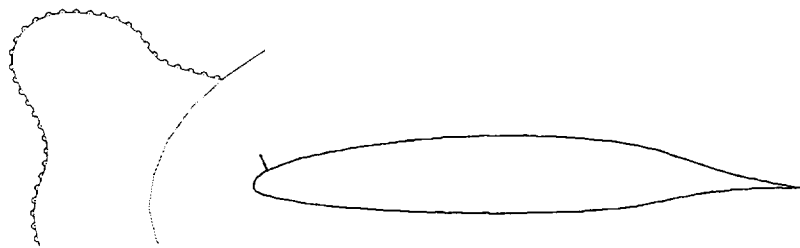


Figure 3. Sample Ice Shape Characterization



- (a) Left--A train of semi-circles on smooth ice to study roughness effects
- (b) Right--A vertical spoiler on a clean airfoil

Figure 4. Artificial ice shapes for parametric study

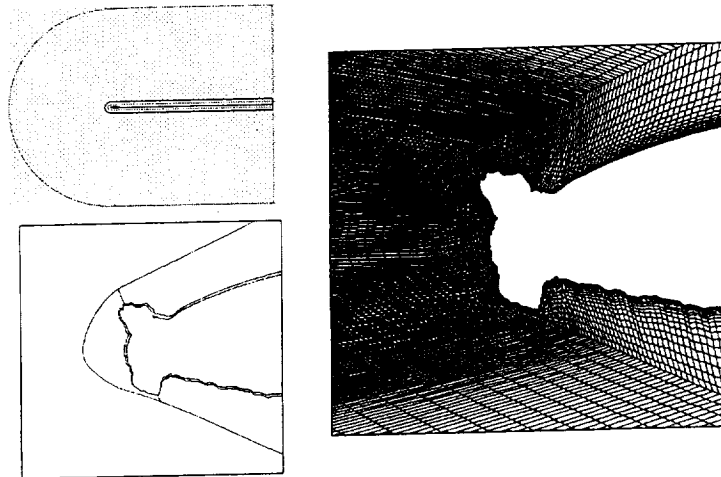


Figure 5. Blocking and grid around the leading edge of the iced airfoil

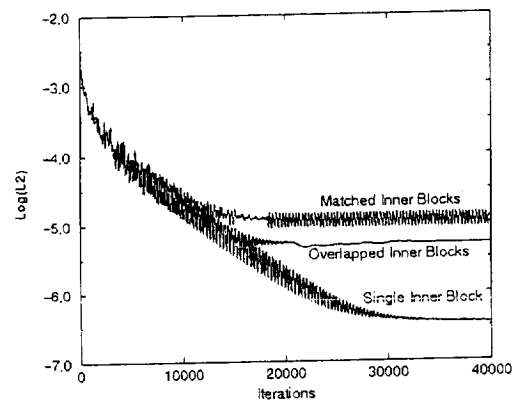


Figure 6. Convergence of single and multi-block inner grids

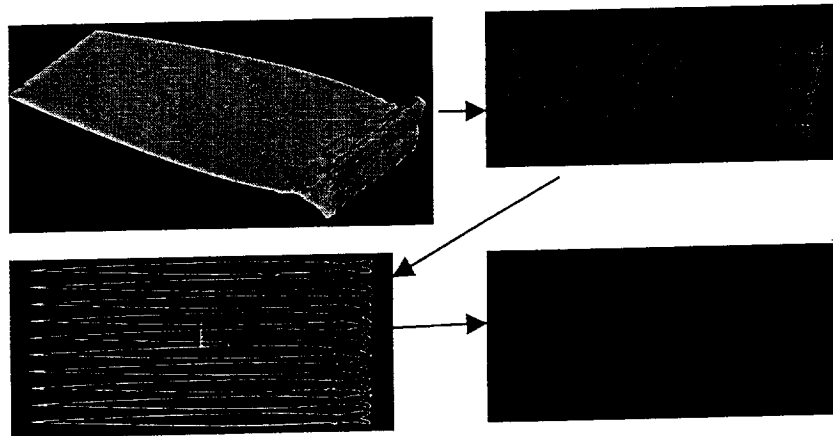


Figure 7. Geometry Acquisition and Modeling

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